Ultrasonic Waveguide Transducer for Under-sodium Viewing in SFR

K. Wang[1], H. T. Chien[2], W. P. Lawrence[3], D. Engel[4], S. H. Sheen[5]

Nuclear Engineering Division, Argonne National Laboratory

9700 S. Cass Ave, Argonne, IL 60439, USA

[1]kwang@anl.gov; [2]htchien@anl.gov; [3]lawrence@anl.gov; [4]engel@anl.gov; [5]sheen@anl.gov

***Abstract*-An ultrasonic imaging system based on the waveguide technique was developed to provide in-service inspection of reactor core and mechanical components in sodium-cooled fast reactors (SFR). By using the ultrasonic waveguide technique, we overcome the major technical challenge in developing an under-sodium viewing (USV) system that can sustain the high-temperature, high-radiation, and corrosive environment. The developed ultrasonic waveguide transducers (UWTs) show high detection sensitivity with minimal background noise by effectively reducing spurious echoes and mode conversions. The performance of UWTs was demonstrated in liquid sodium up to 650°F (343°C). C-scan images of a target were successfully developed from both time-of-flight and amplitude variations of the reflected echoes. The ultrasonic waveguide imaging system demonstrates a capability of detecting defects with 1mm in width and 0.5mm in depth under sodium. The developed imaging system would have broad applications for industries, energy or manufacturing, involving harsh environments.**

Keywords*- *Ulrasonic; Waveguide; Under Sodium Viewing; Molten Sodium; C-scan

I. INTRODUCTION

As one of the advanced reactor designs, Sodium-Cooled Fast Reactor (SFR) has attracted great attention, because of its capability to use available fissile and fertile materials (including depleted uranium) and make it considerably more efficient than thermal spectrum reactors with once-through fuel cycles [1]. But the use of molten sodium as coolant makes it more demanding for the integrity inspection of SFR. A viable under-sodium viewing (USV) instrument must rely on ultrasonic imaging because liquid sodium is optically opaque and electrically conductive.

A USV system can provide an in-service inspection of the reactor core and mechanical components in SFR. USV works usually are conducted during shutdown while sodium temperature is between 200°C and 260°C. Therefore, the major technical challenge developing a USV system is the design of a transducer that can sustain the high-temperature, high-radiation, corrosive environment. Two approaches being pursued are high-temperature transducer development and use of a waveguide. Most of the early works [2, 3] were focused on the development of high-temperature immersion transducers. Ord and Smith [2] developed a spring-loaded ultrasonic transducer operated for more than 1,300 hours in liquid sodium at 260°C. Ultrasonic array transducers were developed to reduce USV inspection time [4,5]. The waveguide approach can employ the commonly used lead zirconatetitanate (PZT) piezoelectric transducer that generally has good sensitivity and a high tolerance to radiation.

Waveguides have been used to deliver and receive acoustic signals in harsh environments for years. A waveguide acts as a buffer that isolates the sensing transducer from a high-temperature and corrosive medium. Because the transducer is kept in a relatively cool environment, below the Curie temperature of its piezoelectric element, the transducer can perform with better reliability. Furthermore, the waveguide design is more suitable for applications with special space requirements, and in general the cost of a PZT transducer is lower than that of a high-temperature transducer. The ideal waveguide transducer must have high efficiency as a transmitter and high sensitivity as a receiver. In practice, the problem of using a waveguide to transmit ultrasonic waves is the presence of spurious echoes resulting from wave dispersion, reverberation, mode conversion, and diffraction within the waveguide. Elimination or reduction of the spurious echoes is the main consideration in waveguide development. Various ultrasonic waveguide designs have been reported [6-9]. However, the *in-situ* evaluations of the proposed designs in molten sodium haven't been reported.

In this work, we develop an imaging system based on the ultrasonic waveguide transducer to provide in-service inspection for SFR. The performance of the 12" (304.8 mm) and 18" (457.2 mm) ultrasonic waveguide transducer (UWT), and the USV system was evaluated in molten sodium up to 650°F (343°C). The results demonstrate that the developed USV system is capable of achieving a lateral resolution of 1 mm and a vertical resolution of 0.5 mm in molten sodium.

II. EXPERIMENTAL SETUP

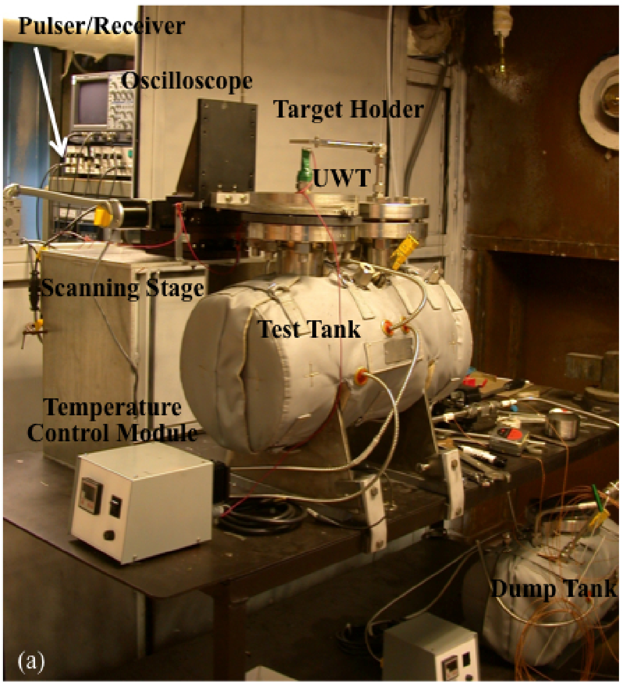
The prototype UWT includes a piezoelectric transducer (5MHz, Aero Tech) and a special designed waveguide (WG), as shown in Fig. 1. Our unique WG is a hybrid of bundle-rod and spiraled-sheet WG design, which can effectively suppress the spurious echoes from wave dispersion, reverberation, and mode conversion. WGs evaluated in this work have a diameter of 0.625(15.9 mm) and a length of 12" (304.8 mm) and 18" (457.2 mm). To enhance the output ultrasonic signal intensity, concave focal lens was fabricated at the end of each WG. The focal lens has an aperture diameter of 0.625" (15.9 mm) and a curvature radius of 1" (25.4 mm).

The performance of the prototype WG was compared with other designs, such as smooth rod WG, threaded rod WG, bundle rod WG, and spiral-sheet rod WG, where the smooth rod WG is a solid stainless steel rod; the threaded rod WG is a solid stainless steel rod with threads (12 threads per 25.4 mm) fabricated along the axial direction of the rod; the bundle rod WG consists of an array of thin stainless steel rods tightly packed inside a stainless steel tube, the diameter of the outside tube is much bigger than that of the thin rods; and the spiral-sheet rod WG is fabricated by wrapping a shim stock around a tube, which facilitates the wrapping process. The spiraled sheet was then inserted in an outer tube with a tight fit and both ends of the rube were welded and polished to flat and in parallel.

Fig. 1 ANL 12" UWT with concave focal lens

The signal to noise ratio (S/N) of the target reflections detected by different WGs, signal attenuation and transmission efficiency through each design was evaluated and compared. Our design has effectively minimized the mode conversion during signal transmission, while maintaining low signal attenuation and high S/N. Details on its performance have been reported elsewhere [10, 11].

To evaluate the UWT in molten sodium, we built an under-sodium viewing test facility, as shown in Fig. 2(a). It consists of a LeCroy oscilloscope (LeCroy 9370), a signal generator and receiver (Panametrics 5058PR), 2D scanning stages, temperature control module, test tank and dump tank.



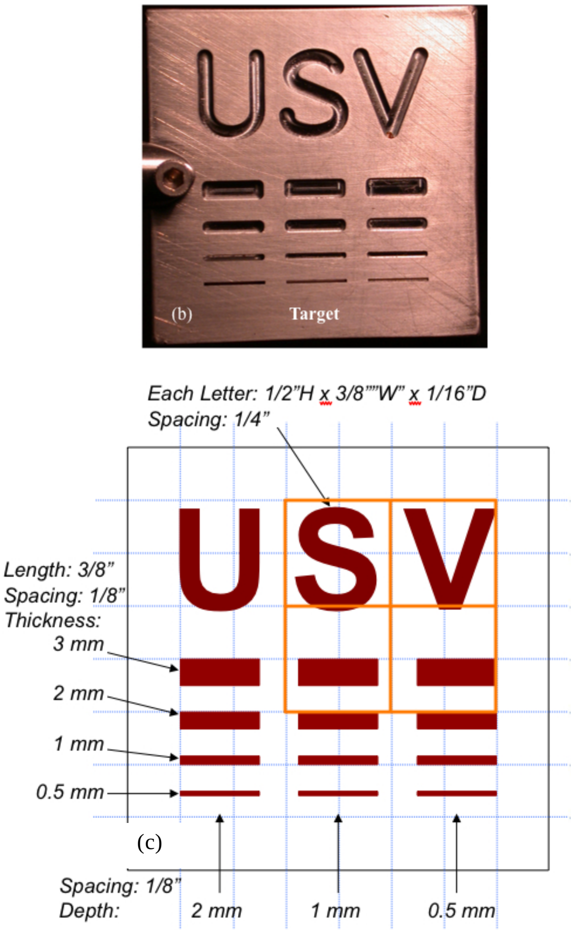


Fig. 2 Under-sodium viewing system and “USV” target

Both tanks are connected to a vacuum pump line and an argon gas supply line. The two tanks are connected through a ½" (12.7 mm) stainless steel tube with Swagelok® VCR face seal fitting. The tube facilitates sodium transfer between the two tanks. Both tanks are placed in drip pans. There are four pressure relief (PR) valves, PR-1 to PR-4; PR-1 is installed in the vacuum line; PR-2 controls the argon gas line; PR-3 and 4 are installed on the tops of sodium vessels. Should overpressure occur in the system, argon gas will be vented to ambient (note that at 200 °C sodium vapor pressure is in 10^{-6} bar). The relief valves ensure that the tank pressure is below 2 psi that is well below the tank design pressure (10 psi).

The USV test tank, as shown in Fig. 2, was built from an 8.0" (203.2 mm) schedule 40 stainless steel 304 (SS 304) pipe to which two 8.0" (203.2 mm) SS 304 schedule 40 caps were welded on both ends. The length of the tank is 20" (508 mm). Each access port on top of the vessel has an opening of 3.07" (78 mm) to which a 5.0" (127 mm) pipe is welded and a 3" (76.2 mm) slip-on flange class 300 is welded on the pipe. The tank was built and tested according to ASME Code Section VIII.

The dump tank, shown in Fig. 2, was constructed in the same way as the test tank. But the total length of the dump tank is 16" and it has only one open port. A maximum of 2.8 gallons of sodium will be placed in the dump tank so that 2.5 gallons of sodium can be transferred to the test tank for USV tests. Both tanks are equipped with sodium level and temperature sensors and a pressure gauge is used to indicate the argon cover gas pressure. Heating jackets specifically designed to fit both tanks were acquired from HTS/ Amptek

Company. The heating jacket has the specifications of 1440W, 120V, with a 2-foot type K thermocouple, 2-foot armoured power leads and two insulated end caps. The heating jackets are controlled by bench-top controllers equipped with the jackets. For over-temperature protection, an independent thermocouple is also provided for each tank to measure the sodium temperature and display it on the control panel. Operators will check the temperature readings during the tests. Heaters to both tanks will be off when unattended.

The two ports on top of the test tank are designated for the target sample (right port) and test UWT (left port). The target sample port allows one to insert the target assembly that consists of a mounting rod and a sample holder to which the target sample is attached. The entire assembly will be installed before sodium loading and will not be removed until the completion of tests. The mounting rod will provide the Z-axis adjustment while the sample holder will position the target directly underneath the test UWT. To facilitate the scanning capability as well as to seal the UWT port, two graphite washers were used. The top graphite washer was attached to the cover flange, which was moved by the 2D scanning stages. Another graphite washer was fixed on the bottom flange of the port. Two graphite washers are in close contact during scanning to ensure the proper sealing of the UWT port. The diameter of the UWT port is only 3" (76.2 mm), which directly limits the maximum scanning area of the 2D stages up to 2" × 2" (50.8 mm × 50.8 mm). For safety concerns, the common scanning area used in the experiment is 1" × 1" (25.4 mm × 25.4 mm) at elevated temperatures.

The scanning stage and data acquisition are controlled by LabVIEW™ program. In the experiment, bottom section of the UWT was immersed into the molten sodium while keeping the transducer outside the test tank. The separation between the target and the end plate of UWT can be adjusted up to 4" (101.6 mm).

A patterned SS plate was used as the target for both under-water and under-sodium imaging test, as shown in Fig. 2(b) and (c). The size is 2"× 2" (50.8 mm × 50.8 mm) with 1/4" (6.4 mm) thickness. The letters "U", "S", "V" and twelve slots with different width and depth were engraved on the plate. Each letter is 1/2" (12.7 mm) high, 3/8" (9.6 mm) wide and 1/16" (1.6 mm) deep. Each row of slots has the same width. From top to bottom, the width is 3 mm, 2 mm, 1 mm, and 0.5 mm. Each column of slots has the same depth. From left to right, the depth is 2 mm, 1 mm, and 0.5 mm. All slots have the same length of 9.5 mm. The slot with 0.5 mm width and 0.5 mm depth is the smallest feature patterned on the target.

III. RESULTS AND DISCUSSION

The under-sodium imaging of the "USV" target was conducted inside the test tank at 650 °F (343°C) using both 12" (304.8 mm) and 18" (457.2 mm) UWT.

A. Radio Frequency (RF) Signal in Molten Sodium

The RF signals of the developed UWT were measured by using 12" WG with 0.5" (12.7 mm), 1" (25.4 mm), 1.25" (31.8 mm), 1.5" (38.1 mm), 1.75" (44.5 mm), 2" (50.8 mm), 2.25" (57.2 mm), 2.5" (63.5 mm), 2.75" (69.9 mm), 3" (76.2 mm), 3.25"(82.6 mm) target-WG end tip separation at 300 °F. The RF signal at 1" separation is shown in Fig. 3. There are two pulse trains observed. The ultrasonic (UT) signal attenuation in molten sodium is calculated based on the following equation:

$$\alpha = -20\log_{10}(V_2/V_1) \tag{1}$$

Where α is the attenuation coefficient, V_1 and V_2 are the maximum peak values in pulse train 1 and 2, respectively. The average attenuation coefficient based on all measurements is 6.6 dB/inch (2.62 dB/cm), which is larger than the reported value (1.75 dB/cm) [12]. We attribute this to the presence of sodium hydroxide flakes. A sodium loop with cold trap to remove sodium hydroxide was not integrated in this experimental setup.

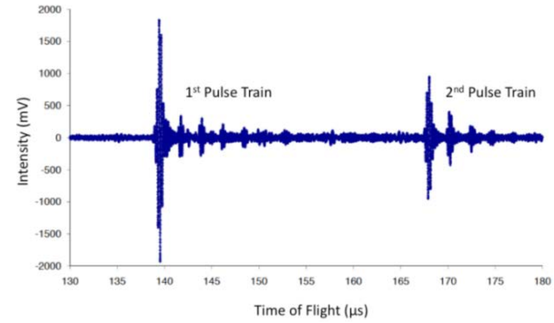
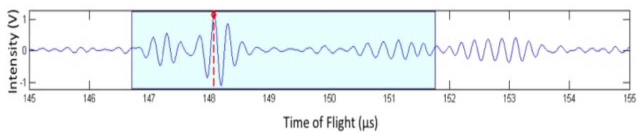


Fig. 3 UT signal of UWT in molten sodium at 1" separation using 12" WG

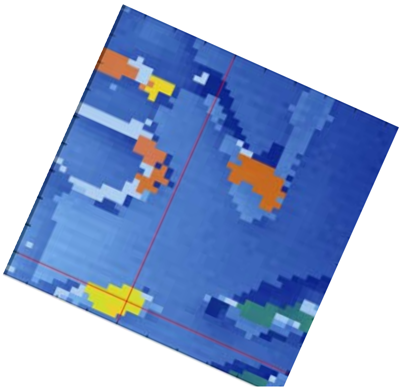
B. Under-Sodium Imaging

The under-sodium imaging using 12" UWT was carried out inside the sodium tank at 650 °F. Results are shown in Fig. 4. During the experiment, the target plate was placed 1.75" (44.5 mm) away from the end tip of UWT, which was at the nominal focal point of the waveguide in molten sodium. The scanning size was 1"× 1" (25.4 mm × 25.4 mm) with a resolution of 50 pixel/inch. The reflected acoustic signal from the target is given in Fig. 4(a) to the crossing point shown at the time of flight and intensity images. The corresponding scanning area is highlighted in Fig. 4(b). Fig. 4(c) and (d) shows the time-of-flight and intensity images respectively. Two reflected echoes can be identified in Fig. 4(a). The first echo at 147.3 µs is generated by the signal reflected from the front surface of the target. The second echo at 148.1µs, in the highlighted region, is risen from the reflection of the signal from the bottom part of grove, which is 1 mm below the front surface. The induced time-of-flight difference of the acoustic signal is 0.8µs, which matches well with the experimental measurement and further confirms that the second echo is caused by the engraved feature.



(a)

(b)



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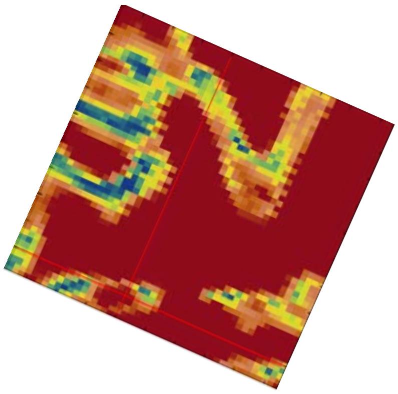
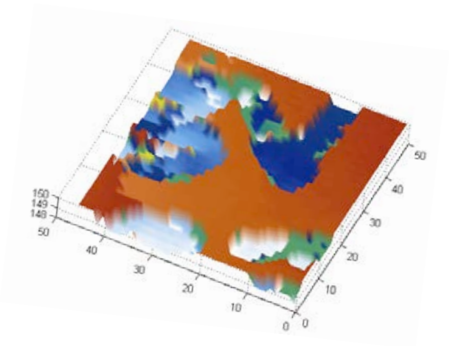


(d)

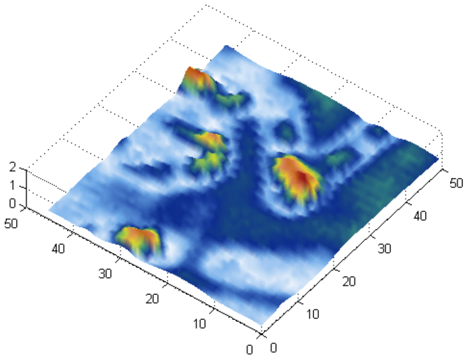
Fig. 4 Under-sodium viewing images using 12" UWT at 650 °F: (a) Acoustic signal reflected from the target at the cross; (b) Scanning area; (c) Time of flight image; and (d) Intensity image

Both echoes were used to construct the time-of-flight and intensity images, as shown in Fig. 4(c), (d). From these images, letters "S", "V", slot with 1 mm depth and 3 mm width, slot with 0.5 mm depth and 3 mm width, and part of slot with 0.5 mm depth and 2 mm width are clearly identified. These results manifest that our 12" (304.8 mm) prototype waveguide is able to achieve a vertical resolution of 0.5mm and a lateral resolution of 1 mm in molten sodium.

Furthermore, 3D images were plotted for time of flight and intensity results as shown in Fig. 5(a) and (b). For time-of-flight 3D image, the x-axis and y-axis are scanning coordination; z-axis is the travel time (μs) of the reflected signal. For intensity 3D image, z-axis is the amplitude (V) of the reflected signal. As seen in both of the images, the developed waveguide transducer is able to identify 0.5 mm depth in vertical direction, which is equal to the wavelength of ultrasonic signal at 5 MHz in molten sodium.



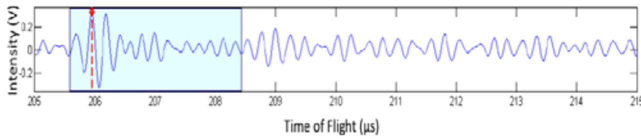
(a) Time-of-flight 3D image



(b) Intensity 3D image

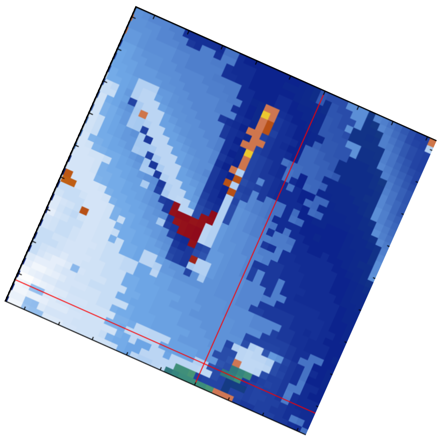
Fig. 5 3D under-sodium viewing images using 12" WG

The under-sodium imaging using 18" UWT was also carried out inside the sodium tank at 650 °F (343°C). Results are shown in Fig. 6. The experimental conditions are identical with those of 12" UWT under-sodium viewing experiment. Comparing with the results of 12" UWT, the signal intensity of 18" UWT is lower, mainly due to higher signal attenuation along the longer WG used. Consequently, the image quality is not as good as that of 12" UWT. But letter "V" and part of the slot with 0.5 mm depth and 3 mm width are still apparent in the imaging results.

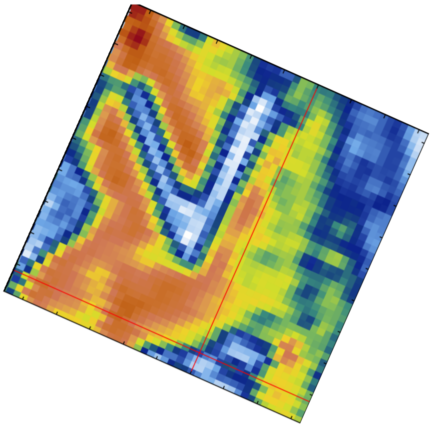


(a)

(b)



(c)



(d)

Fig. 6 Under-sodium viewing images using 18" UWT at 650 °F. (a) Acoustic signal reflected from the target at the cross; (b) Scanning area; (c) Time of flight image; and (d) Intensity image

C. Evaluation on the Focusing Capability of UWT

We evaluate the focusing capability of the developed UWT both theoretically and experimentally at an ultrasonic frequency of 5 MHz. Based on Kino's work [13], the lateral resolution, *dr*, and focusing depth, *dz*, can be calculated using the following equations:

$$dr \approx 1.02\lambda(F/D) \tag{2}$$

$$dz \approx 7.1\lambda(F/D)^2 \tag{3}$$

Where λ is the wavelength of ultrasound in molten sodium, *F* is the focal length and *D* is the aperture diameter of the lens. λ and *F* are calculated using equations:

$$\lambda = v_{Na}/f \tag{4}$$

$$F = \frac{R}{1-(\frac{v_{Na}}{v_{SS}})} - \frac{d(\frac{v_{Na}}{v_{SS}})}{2(\frac{v_{SS}}{v_{Na}}-1)} \tag{5}$$

Where *v* is the longitudinal wave velocity; *R* is the curvature radius of the lens, and d is the diameter of the transducer. For small aperture radius, the second term in Eq. (4) can be ignored. The value of v_{Na} and v_{SS} at 650 °F (343°C) are 5,573 m/s [14] and 2,394 m/s [15], respectively. The calculated values of *F*, *dr* and *dz* are summarized in Table I.

TABLE I THEORETICAL EVALUATION OF THE FOCUSING CAPABILITY OF THE DEVELOPED UWT IN MOLTEN SODIUM

	Focusing Capability of the Developed UWT in Molten Sodium at 650 °F
F (mm)	42.0
dr (mm)	1.3
dz (mm)	26.7

In the experiment, the strongest reflected ultrasonic signal intensity was observed at 1.5" (38.1 mm) and 1.75"(44.5 mm) target-WG separation, which matches well with the theoretical focal length of UWT in molten sodium. The lateral resolution in experiments is 1 mm, smaller than the theoretical value. This indicates that the sizing capability of UWT is not only determined by the parameters described in Eq. (2), other factors, such as reflected signal intensity, signal to noise ratio, and the ratio between signals reflected from flat surfaces and engraved regions, also play critical roles in determining the detection resolution of UWT. Efforts are presently underway to conduct further analysis to optimize the signal-processing algorithm.

IV. CONCLUSIONS

Bench scale sodium test facility was designed and constructed for demonstration of under sodium imaging using Argonne prototype waveguides. The prototypes show high detection sensitivity with minimal background noise by effectively reducing spurious echoes and mode conversions. These ultrasonic waveguide transducers were further tested in liquid sodium up to 650°F (343°C). The UWT imaging system demonstrates a capability of detecting defects with 1mm in width and 0.5mm in depth under sodium.

We also demonstrate that waveguide with length 18" is possible for USV application. To optimize the UWT for in-service inspection applications inside nuclear reactor core, several issues, such as transducer and waveguide coupling technique, design of focus lens, and signal processing algorithm, need to be further evaluated. Beside defect detection, the developed technique is also capable of monitoring reactor fuel or component replacement process for both SFR and other types of nuclear reactors.

ACKNOWLEDGMENT

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